MONTHLY
WEATHER
REVIEW

VOLUME 92, NUMBER 2
FEBRUARY 1964

ASPECTS OF HURRICANE STRUCTURE: NEW MODEL CONSIDERATIONS SUGGESTED BY TIROS AND PROJECT MERCURY OBSERVATIONS

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ABSTRACT

Satellite photographs of hurricanes reveal the complete storm in relationship to its environment. In many instances "outer convective bands" or "pre-hurricane squall lnes" appear to partially "ring" the storm. These bands are usually separated from the rim of the high cloud shield by a relatively clear channel, visible and distinct for long distances along the circumference. This channel may be formed through the action of a major subsiding branch of the hurricane's circulation. Many photographs also reveal extensive areas of convective, cirrus-producing cloudiness in the wake of the storm. This cloudiness appears to be intimately associated with that of the hurricane, and strongly influenced by outflow effects. Time cross-section analyses of hurricanes Carla and Anna suggest peripheral subsidence. The area of possible subsidence, in both instances, occurred under an upper shear line, where air diverging in the outflow layer from the hurricane converged with air emanating from the subtropical High. A jet stream, in the case of hurricane Carla, appeared in the region of the subsident annular zone, at the edge of the high cloud shield. This high speed current curved anticyclonically along the northern quadrants of the storm—then, on being directed southward, split into two main branches. The eastern branch curved cyclonically into a trailing vortex, apparent as a cold Low at 200 mb. The western branch continued southward, in alignment with the curvature of cloud streaks forming the cirrus "tail" of hurricane Carla. These features appear to be typical of many hurricanes in certain stages of development. Model considerations, employing these features, with a discussion of ramifications, are suggested in this paper.

1. INTRODUCTION

TIROS III photographs of hurricane Anna (fig. 1) on July 22, 1961 and Project Mercury photographs of hurricane Debbie (fig. 2) on September 13, 1961, reveal the presence of a relatively clear annular zone [2] along the periphery of the high cloud shield of each storm. In the Mercury photographs, traces of the lower cloud field can still be seen in the annular zone. Low clouds again appear under the edge of the high cloud shield, visible through breaks in the upper cloudiness. It is of particular interest that row alignment appears to be maintained parallel to that previously established in outlying areas. The implication is that fairly intense subsidence occurred, in a narrow zone at the edge of the high cloud shield, and was imposed on the existing lower-level flow. It will be noted that a suggestion of a subsident zone is apparent over the entire southern boundary of hurricane Anna. Other satellite pictures, notably a TIROS III view of hurricane Esther on September 16, 1961 (fig. 3) and a TIROS V view of typhoon Ruth on August 15, 1962 (fig. 4), have shown marked annular zones along the northern boundaries of storm cloudiness. The quadrant or quadrants of occurrence of this feature do not appear to be related in any obvious or easily applied manner to direction of storm movement, but the feature is seen frequently enough to justify the impression that it may be an important manifestation of the hurricane's circulation.

Another noteworthy feature appearing on the photographs is the presence of a curved line of intensified

[1] Capt., USAF

[2] The term "annular zone" or "annulus", as used in this paper, refers to the relatively clear or cloud-free strip (especially free of lower clouds) adjacent to the rim of the high cloud shield of the hurricane, along any portion of its circumference. It will be shown that this is an *annular zone of subsidence*.

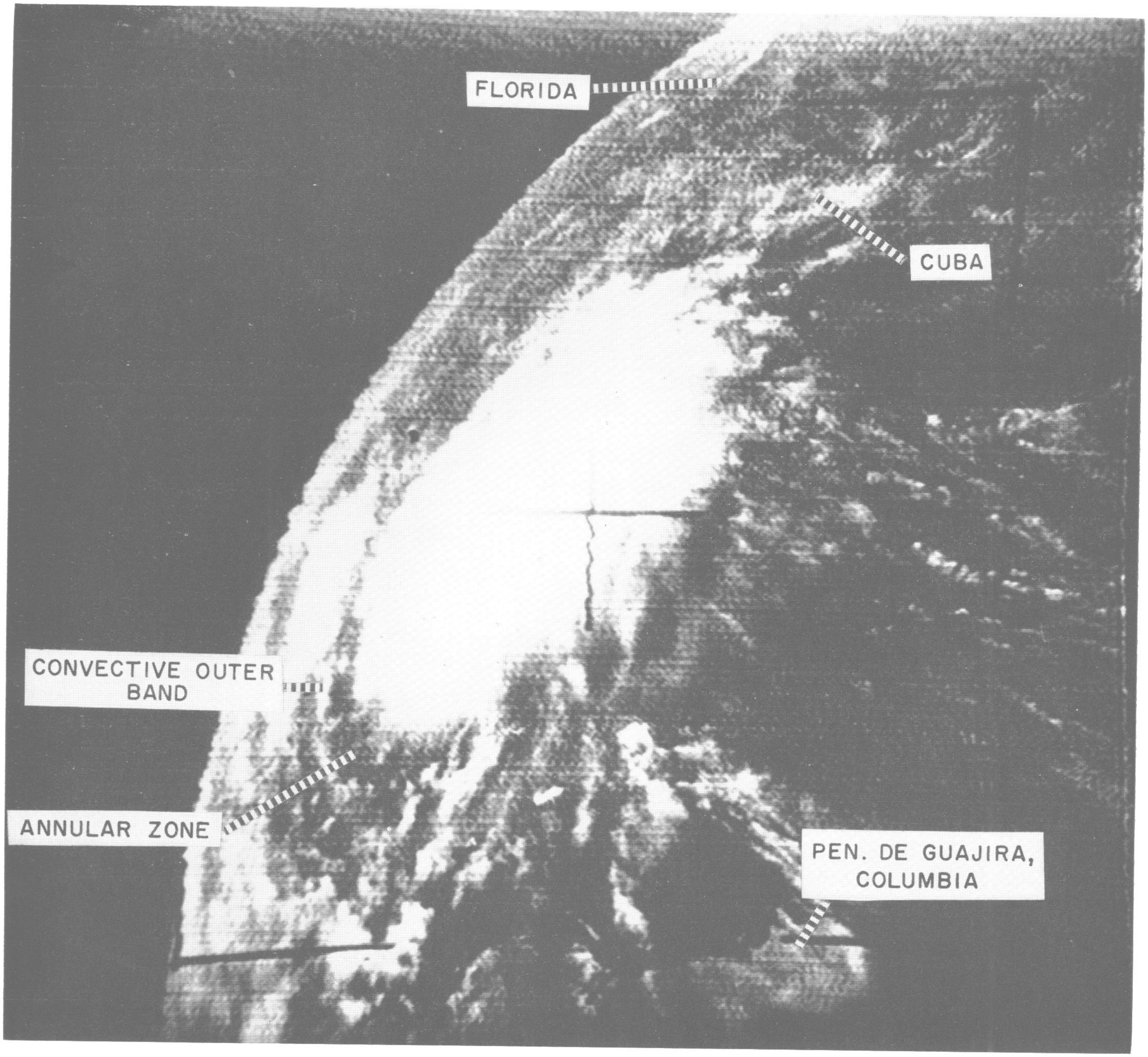

FIGURE 1.—TIROS III view of hurricane Anna at approximately 1500 GMT, July 22, 1961. View is to the north-northwest. Storm was moving westward toward lower central portion of horizon.

convection at the outer edge of the annulus and paralleling the curvature of the rim of the high cloud shield along the edges of the storms. When the Mercury photographs (fig. 2) were viewed stereoscopically, cloud tops of the outer convective band were determined to be at an altitude of 15000–16000 ft., well above the other more suppressed cloud lines. Other TIROS hurricane and typhoon photographs suggest that these lines at times develop to full squall line intensity. Figure 5 is a TIROS V picture of typhoon Sarah, taken on August 16, 1962, which shows very clearly the development of a line of convective cloudiness along the northeastern edge of this storm. Cirrus cloudiness, from the high cloud shield, extends over the annular zone, merging with the cloudiness of the convective band. As to the question of proper interpretation of the convective nature of this cloudiness, this interpretation may be deduced from many of the published satellite studies now available [2]. In the case of figure 5, convective cloudiness was also verified through surface reports at Okinawa, located just on the north side of the band [7]. However, it is true that cirrus bands have been reported at the very edge of the hurricane

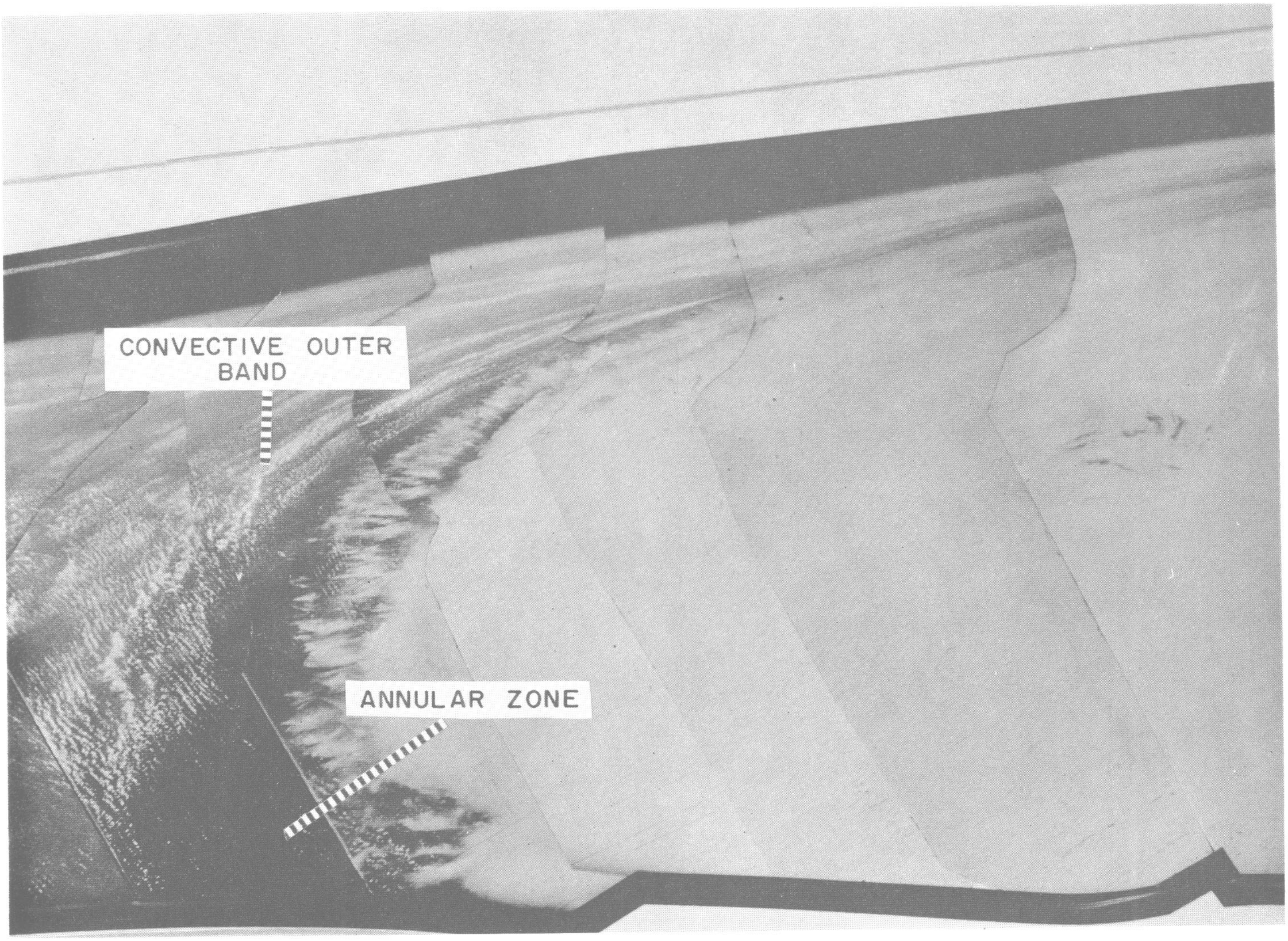

FIGURE 2.—A mosaic of NASA Project Mercury photographs of hurricane Debbie (northwest quadrant), taken at approximately 1415 GMT, September 13, 1961. Storm was moving toward the northeast.

circulation with an apparent absence of any convective cloudiness, as for example in figure 4. With a good viewing angle and fair quality pictures there is no difficulty in differentiating between the cirrus cloudiness and the convective band or squall line. Figure 6 is a mosaic showing typhoon Carmen on August 15, 1963. A cirrus band of the type commonly associated with a jet stream appears along the northern edge of this storm.[3] Note the much fainter reflectivity of this band as opposed to the convective bands nearer the center of the storm and also those farther to the north. The characteristic texture of cirrus as opposed to the much brighter globular patterns of cumulonimbus make it an easy matter to differentiate between the two. Figure 7 is an unusually good example showing a pre-hurricane squall line associated with tropical storm Thelma on August 21, 1962. Again there is no difficulty in deducing the convective nature of this cloudiness.

[3] See section 3 regarding implications of the jet stream in this location.

Historically, of course, many eye witness accounts have testified to the prevalence of pre-hurricane divergence. Unusually clear days followed by a sudden onslaught of hurricane conditions as the "bar" of the storm passed over the station, have been widely quoted in literature. In a pre-satellite study, the appearance of an absolutely clear and persistent strip along the southwestern edge of hurricane Daisy, in what presumably would be the annular area, was noted by Malkus, Ronne, and Chaffee [10]. In this same study a persistent band of cumulus congestus was found 260 n. mi. west of the hurricane center oriented north-south. This corresponds very closely with the location and orientation of the band appearing on the picture of hurricane Debbie (fig. 2). National Hurricane Research Project films of hurricane Cleo, 1958, also show a narrow, cloudless strip at the edge of the high cloud shield of this storm. A line of towering cumulus appears just outward from this strip. Radar studies have shown that "pre-hurricane squall lines" frequently developed in pe-

FIGURE 3.—A mosaic and nephanalysis of a TIROS III pass over hurricane Esther on September 16, 1961. The Great Lakes are clearly visible in the top portion of the mosaic. The storm was moving toward the west-northwest.

ripheral areas. Senn, Hiser, and Low [13] have shown that these lines are typically located 100 to 400 mi. in advance of the center of the storm. These lines are not always characterized by the same spiral curvature as the interior bands, according to their account, and, also unlike the interior bands, individual echoes usually show little tangential motion relative to the storm centers.

These are important aspects which suggest that a major feature of the storm's general circulation may be involved, causing continual regeneration of the cloud elements which make up the band, and maintain it for long periods in the same relative position. The TIROS observations, showing outer convective bands in close proximity to the subsident annular zones, suggest that the two may be

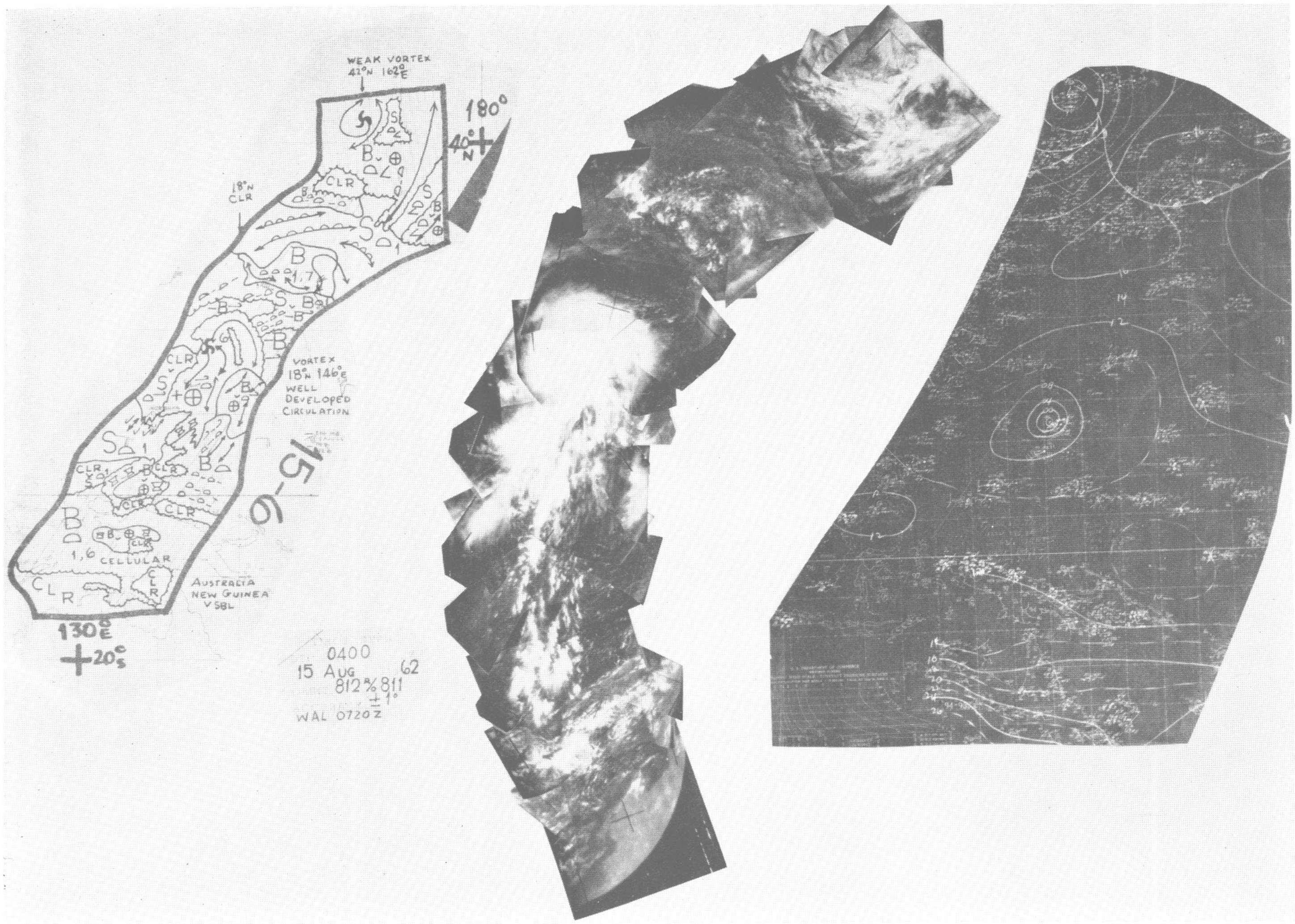

FIGURE 4.—A mosaic and nephanalysis of a TIROS V pass over typhoon Ruth on August 15, 1962. A surface analysis for 0000 GMT, August 15, is also shown. The storm was moving toward the northwest.

related. Such a relationship has certainly never before been proposed. In fact, the idea of major subsidence in the area of a hurricane poses certain problems which Riehl [11] has considered in some detail. He showed that a hurricane circulation could not exist as a closed system. Subsiding effects, in a closed system, could account for the cloudless annular zone at the periphery of the storm. The major point of his argument, however, was that dry adiabatic warming in the subsident branch of this system would soon destroy the solenoidal field necessary for hurricane maintainance, and bring the circulation to a halt. His argument does not appear to preclude the possibility that an important subsiding branch of the hurricane circulation could exist without involving the implications of a closed system. This has been suggested in at least one paper [5] interpreting the TIROS I photograph of a hurricane near New Zealand. The model hurricane circulation proposed by Bergeron [1] also incorporates a major subsident branch at the edge of the storm.

It is the object of this paper to present a more complete interpretation of the new satellite evidence, by relating the TIROS photographs to conventional information available. Relationships suggested in this comparison will be explored in a preliminary and primarily descriptive manner. For this purpose, time cross-section and allied analyses will be presented for hurricanes Carla and Anna of 1961.

2. FORMATION OF HURRICANE CARLA AND RELATIONSHIP TO UPPER SHEAR ZONE

Carla formed from a perturbation which had its origin in the equatorial-trough zone. The National Meteorological Center's Northern Hemisphere Surface Chart of 1800 GMT, September 2, 1961 (fig. 8) shows the position of this zone at approximately 12°N., oriented generally east-west. Also apparent on this chart is the warm Bermuda High pushing strongly into the southeastern United States and extending into the Gulf of Mexico. This High extended well into the upper atmosphere and

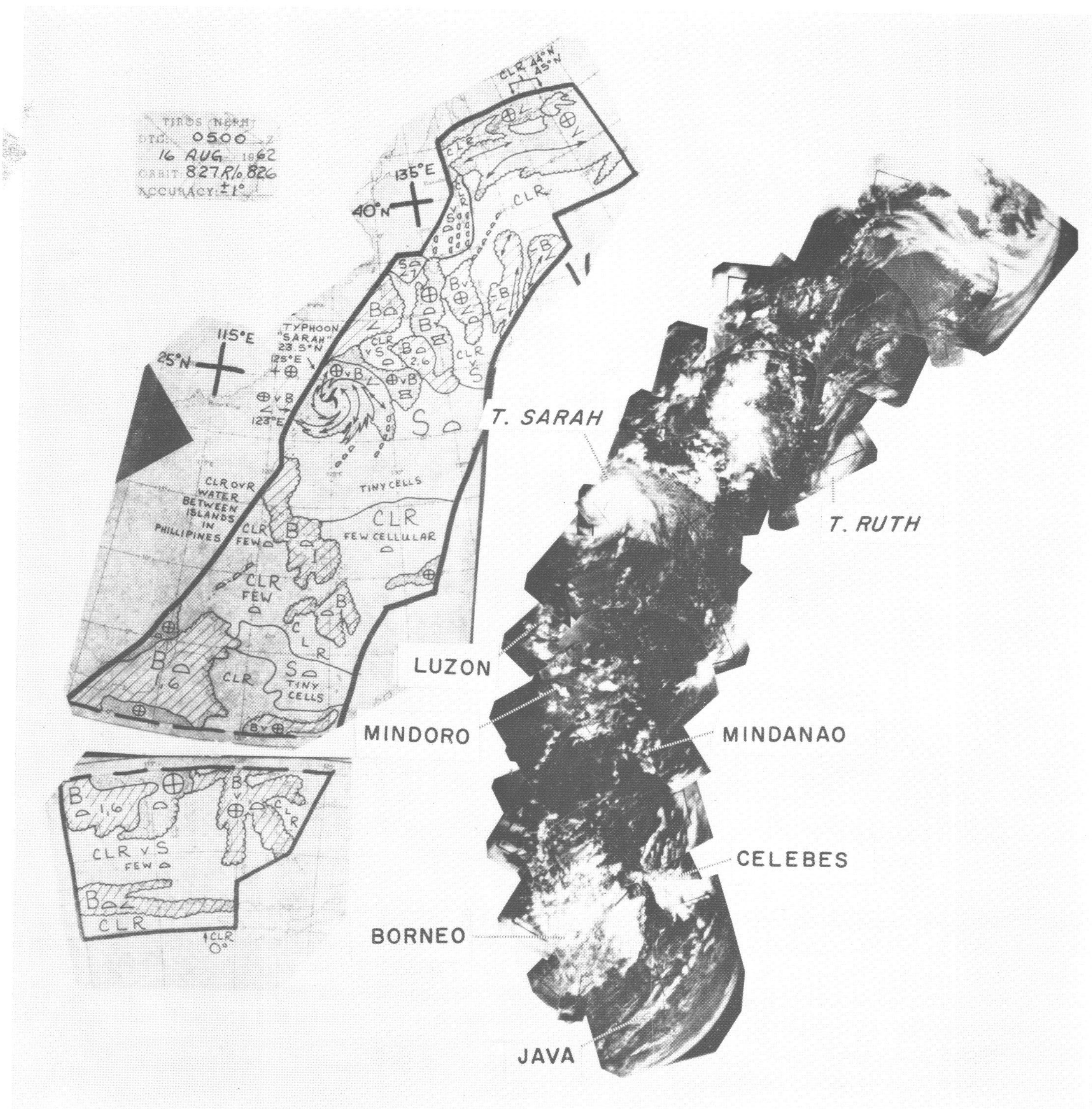

FIGURE 5.—A mosaic and nephanalysis of a TIROS V pass over typhoon Sarah on August 16, 1962. The storm was moving northward.

diverging winds from a center over the United States were evident at the 200-mb. level. The equatorial trough, in this instance, disappeared rapidly with height, and was replaced by a High at upper elevations. Winds also diverged from this center aloft. The 200-mb. analysis of 0000 GMT, September 3, 1961 (fig. 9), shows a shear line over central Cuba, oriented northeast-southwest. Here the diverging winds from the High to the north clashed with those emanating from the High above the equatorial trough. An Atlantic shear line of this type, in the same region, has been described by Riehl [12].

In a manner similar to that described by Riehl, as the hurricane moved northward, the shear line at upper elevations moved northward, maintaining a position approximately 10° latitude in advance of the surface center.[4]

[4] Movement of shear lines in advance of typhoons Sarah and Ruth, 1962, has also been documented in another report [7]. See also shear line development in a study by Frank [8].

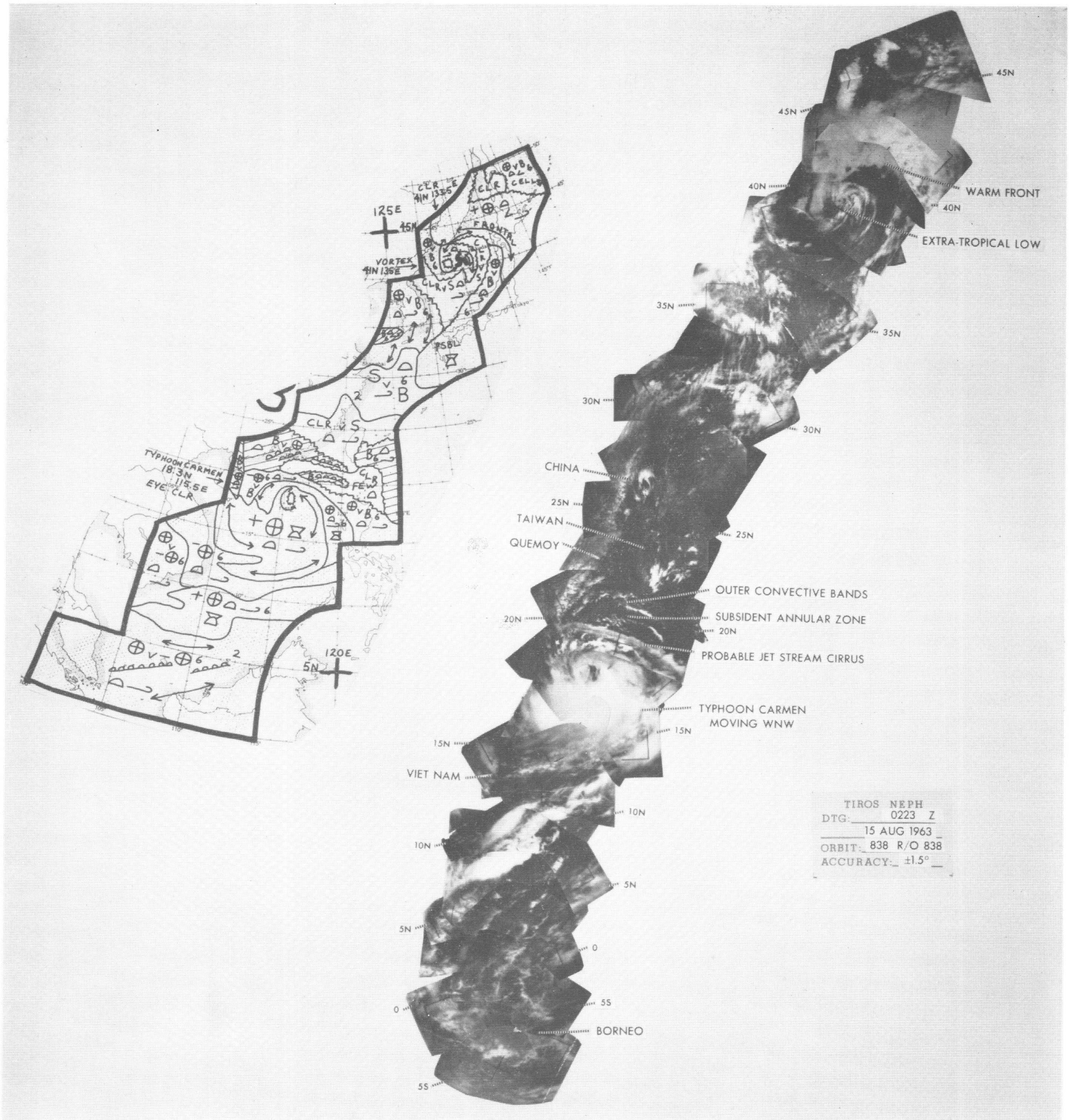

FIGURE 6.—A TIROS VII mosaic showing typhoon Carmen at 0223 GMT, August 15, 1963.

Progressive locations of this line at upper levels and the surface track of Carla, in its various stages, are shown in figure 10. Apparently the position of the shear line was strongly influenced by the movement of the hurricane or vice versa. The shear line, in fact, may have resulted as storm outflow effects were impressed upon the existing circulation. The earlier stages certainly provided extremely favorable conditions for hurricane formation since the anticyclone aloft over the equatorial trough provided a ready-made mechanism for the evacuation of any lower-level inflow.

3. TIME CROSS-SECTIONS AND ALLIED ANALYSES OF HURRICANE CARLA

In order to determine whether subsidence could be detected along the periphery of the high cloud shield,

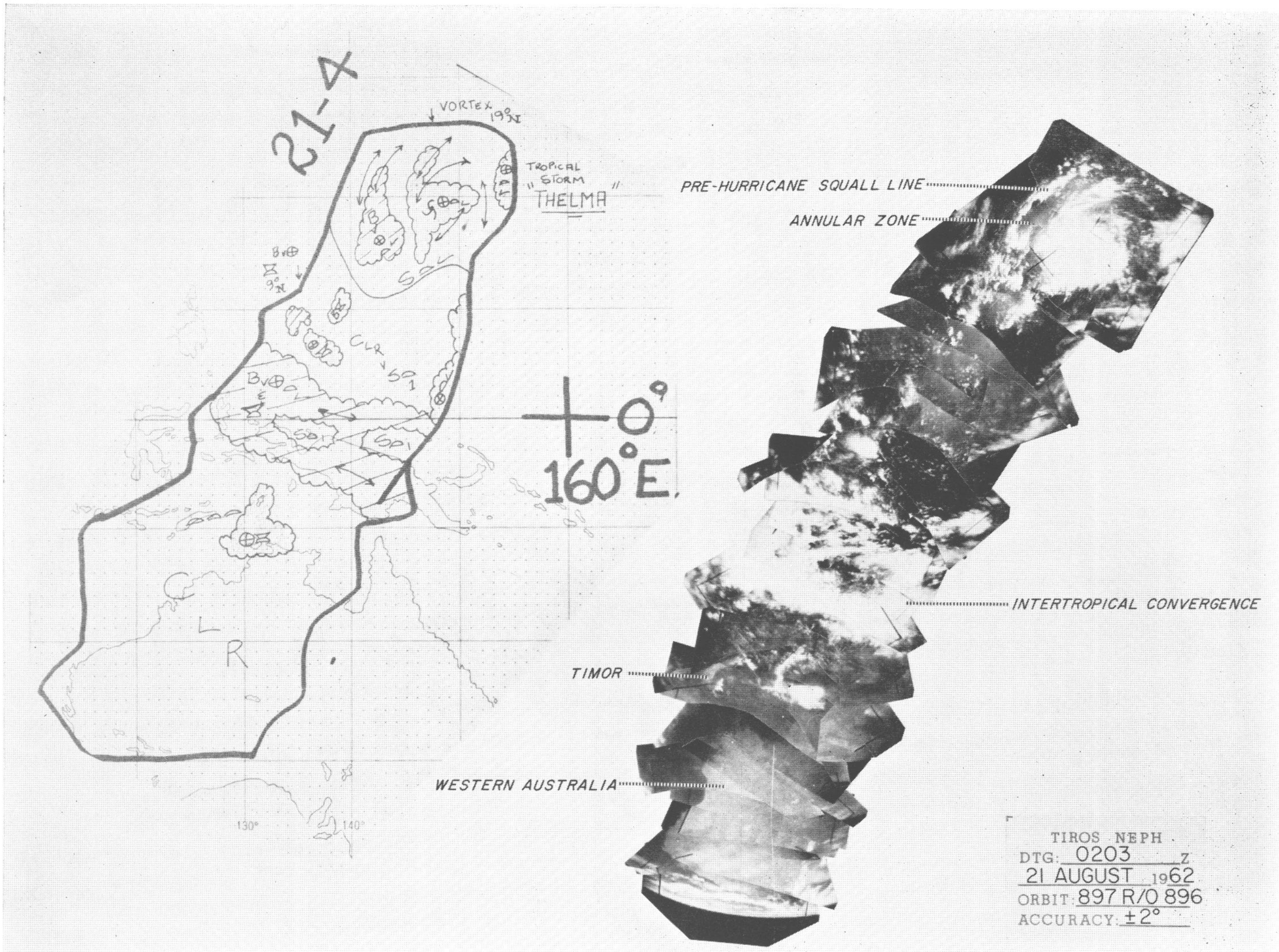

FIGURE 7.—A TIROS V mosaic showing tropical storm Thelma at 0203 GMT, August 21, 1962.

time cross-sections were prepared for some of the stations along the path of the storm.

The first station considered, which experienced passage of the high cloud shield of hurricane Carla, was Havana, Cuba (fig. 11). As shown by the Havana cross-section on September 3, 1961, and by the observations for the preceding days, deep easterlies prevailed over the station at all levels for several days prior to September 4, 1961. Winds aloft are missing on September 4 but by 0000 GMT, September 5, winds in the layer from 300 mb. to at least 150 mb. had shifted from a northeasterly to a southwesterly direction, indicating passage of an upper shear zone at some time prior to that observation. The line at upper elevations in figure 11 denotes the 360°–180° isogon separating easterly from westerly flow. The leading edge of the westerlies, on the cross-section, corresponds to the position of the shear line indicated over Havana by 0000 GMT, September 4, in figure 10. This is the most probable time of passage based on continuity considerations and correspondence with other observations. The westerly belt appears to overlie a large portion of the hurricane circulation, and its center position corresponds very closely to the time of closest approach of Carla to Havana, at 1800 GMT, September 7. Below the westerly belt, at either end, appreciable dryness is indicated by dew point spreads in excess of 15° C. This is also shown, more reliably, in the specific humidity analysis of figure 12. Coincident with this dryness, surface reports indicated generally clear to scattered cloudiness conditions. But inward, toward the storm center, generally moist and overcast conditions prevailed. The moist soundings, it will be noted, did not merely reflect the presence of heavy precipitation areas. Similarly, the dry areas, with dew point spreads in excess of 15° C. were certainly unusual, and a wide departure from the "normal tropical atmosphere". Evidently the major hurricane cloudiness was confined within the limits prescribed by the dry zones at either end, and the westerlies aloft.

The coincidence of such dryness with the arrival of an upper shear zone, suggests that this zone might also have

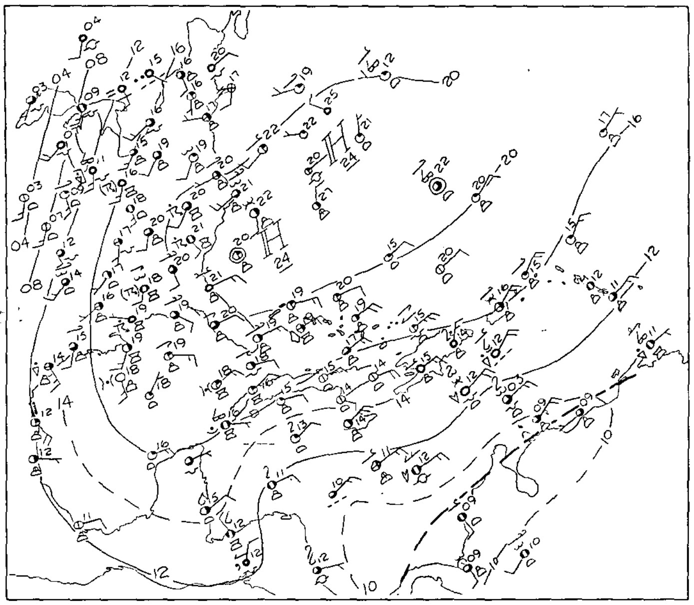

FIGURE 8.—NMC Northern Hemisphere surface chart for 1800 GMT, September 2, 1961.

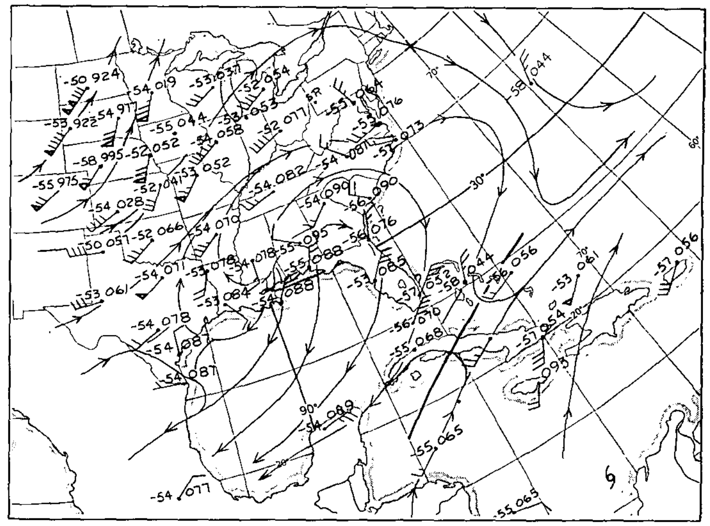

FIGURE 9.—200-mb. streamline analysis for 0000 GMT, September 3, 1961. Shear line is drawn in heavy black over Cuba.

been one of appreciable convergence. The dryness, according to this argument, would have resulted from subsidence in response to the upper convergence. If this were true, then, under the shear zone, warming should be evident, depending on the subsident intensity. An analysis of 24-hr. temperature changes (fig. 13) shows temperature increases at most levels during the period of passage of the leading edge of the shear zone.[5] In particular, the 24-hr. period ending 0600 GMT, September 5 showed temperature increases, through a deep layer below the shear line, to a maximum increase of 4° C. At the same time, height rises in pressure surfaces occurred at upper elevations, in spite of steadily dropping surface pressure (figs. 11 and 12). All of these indications suggest that this was, indeed, a region of fairly intense subsidence. It appears unreasonable to assume that the dryness could have arrived over the station advectively, after a long trajectory over an oceanic area, and still have maintained the temperature distribution observed. Temperature increases similar to those observed, particularly in the lower and middle troposphere, according to Dunn and Miller [3], are "mostly dynamic in origin". The timing of this particular temperature increase, during a period of minimum cloudiness, and just prior to probable time of passage of the edge of Carla's high cloud shield at 1200 GMT September 5, relates well to the type of conditions one might anticipate according to the TIROS views of the annular zone. General warming also occurred on September 12 and may again reflect a peripheral subsident tendency.

[5] Warming, prior to passage of the shear zone, on September 3 occurred after passage of a trough. Warming on September 7 occurred during the closest approach of Carla to Havana, reflecting central warm core characteristics.

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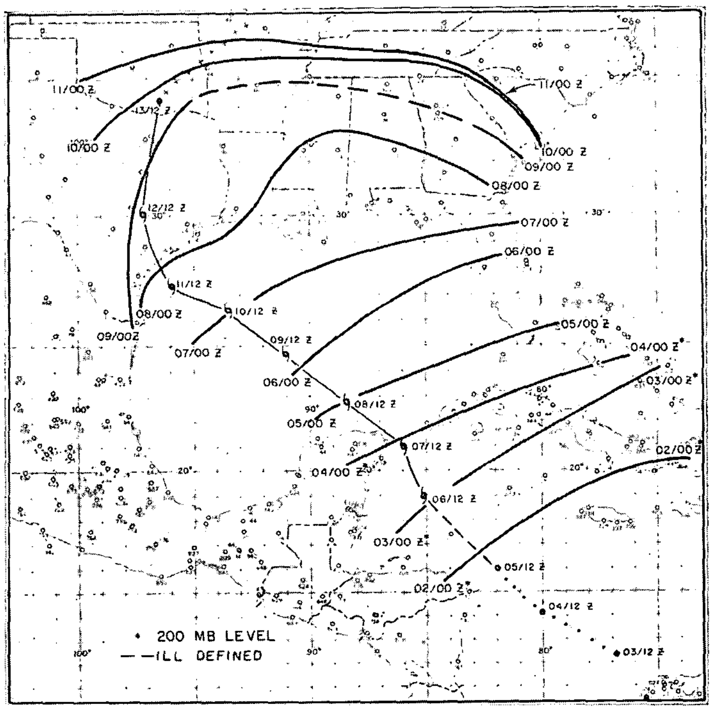

FIGURE 10.—Progressive locations of upper shear line in association with the track of hurricane Carla. Asterisk designates 200-mb. shear line position. All other positions are for the 300-mb. level. Hurricane stages: tropical depression (development) (dotted line), tropical storm stage (dashed line), hurricane stage (solid line), and extratropical stage (line of crosses).

Another aspect, pointed up by the time-section and associated with the location of the shear zone over the annulus of subsidence, appears to be of primary importance. The thermal gradient aloft would have a tendency to be increased in this area. This would occur as warm, diverging, upper-level winds from the hurricane merged with the cooler air flowing outward from the

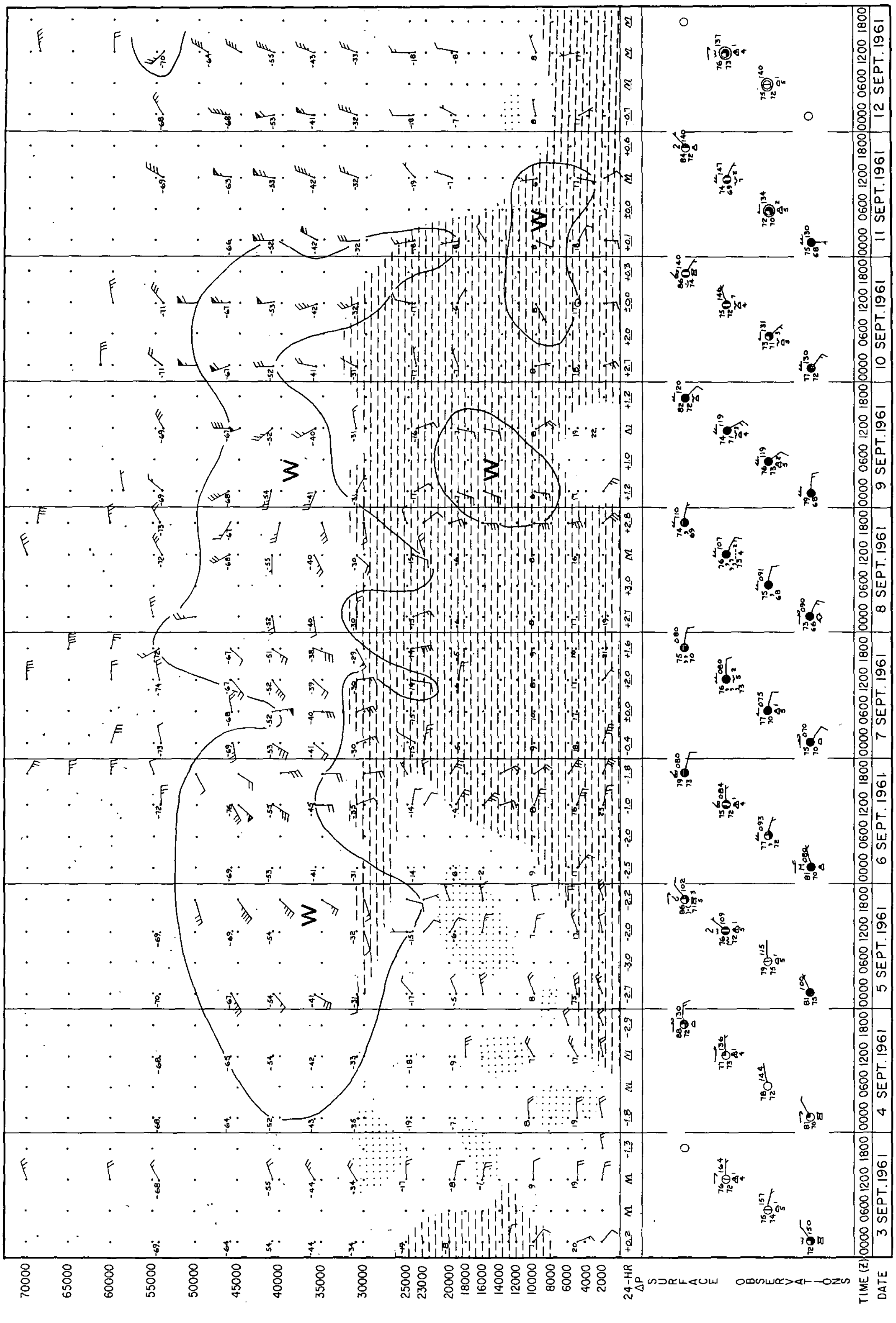

FIGURE 11.—Time cross-section for Havana, Cuba. 24-hr. pressure changes are plotted in the middle of the 24-hr. period. Dashed horizontal lines indicate areas with dew point spreads of 5°C. or less. Dotted areas represent dew point spreads of 15°C. or greater. Clear areas, generally below 30,000 ft., have dew point spreads between 5° and 15°C. The 360°-180° isogon is drawn separating easterly from westerly flow.

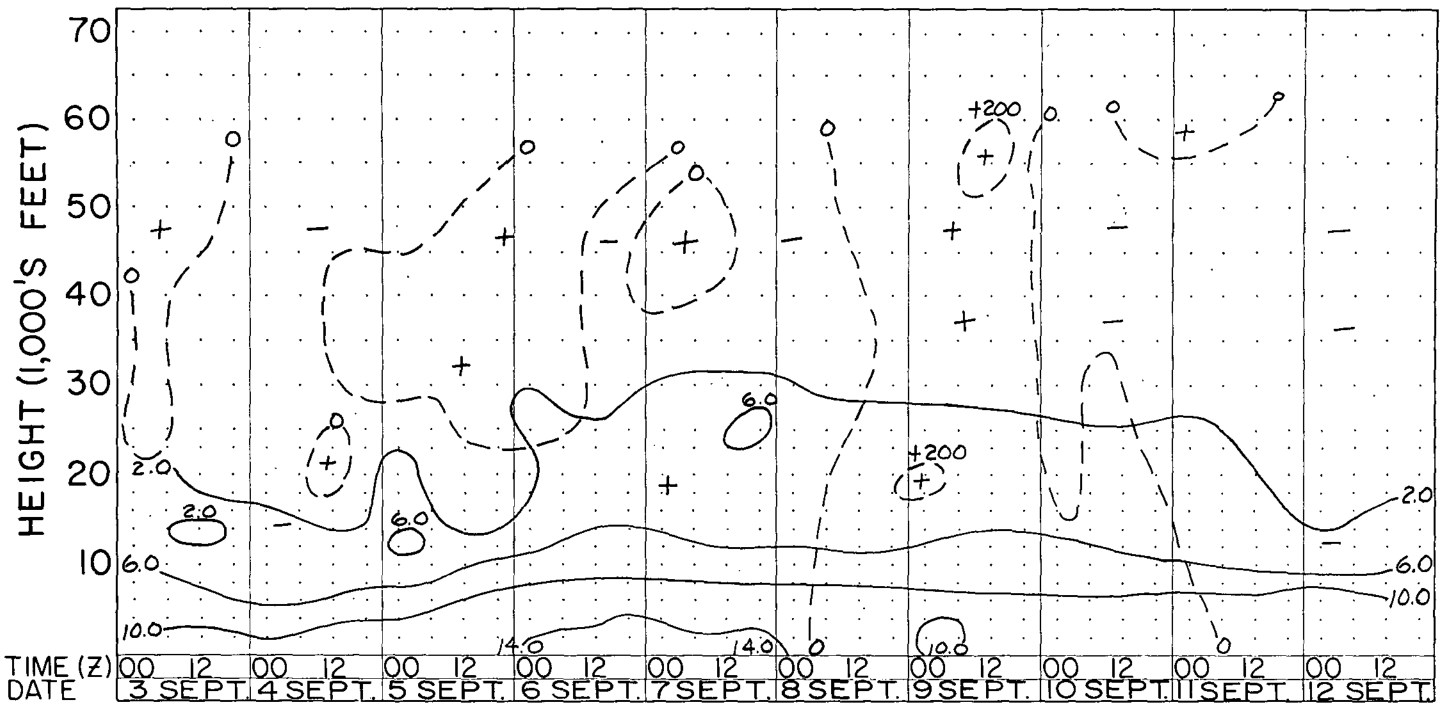

FIGURE 12.—An analysis of specific humidity (mixing ratio) values, over Havana, Cuba, in gm. of water vapor per kgm. of dry air. 24-hr. height changes were plotted in the middle of the 24-hr. period and analyzed (dashed lines) in 200-ft. increments.

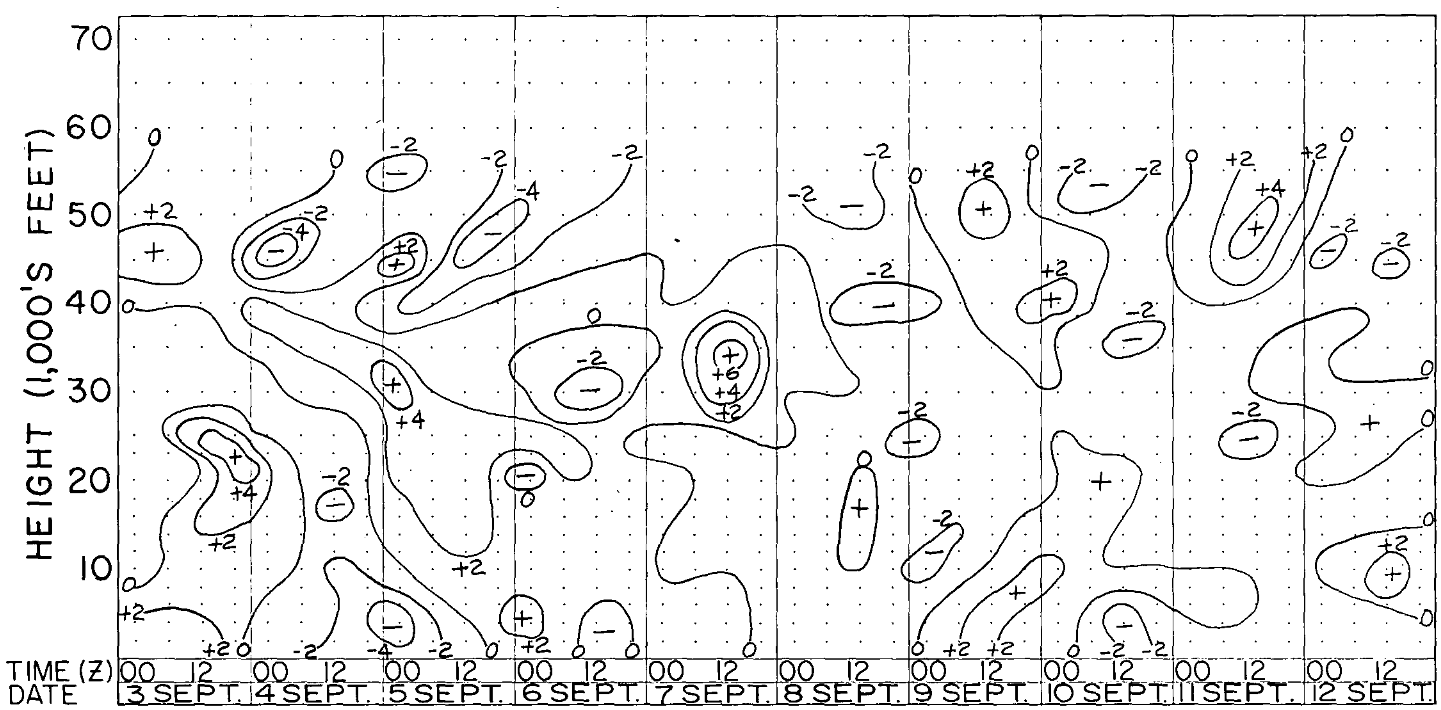

FIGURE 13.—24-hr. temperature change analysis for Havana, Cuba. Isopleths are drawn for point changes of 2°C.

subtropical High. Additional warming through subsidence adjacent to outer convective bands of appreciable upward vertical motion would tend further to intensify the thermal gradient over a very narrow zone. Similar mechanisms have long been considered favorable for the production of a jet stream aloft. It is of interest, in this respect, to note the rapid decrease in the speed of the easterlies with height on Havana's 1800 GMT sounding of September 5. This sounding was made shortly after passage of the high cloud shield over the station. Wind

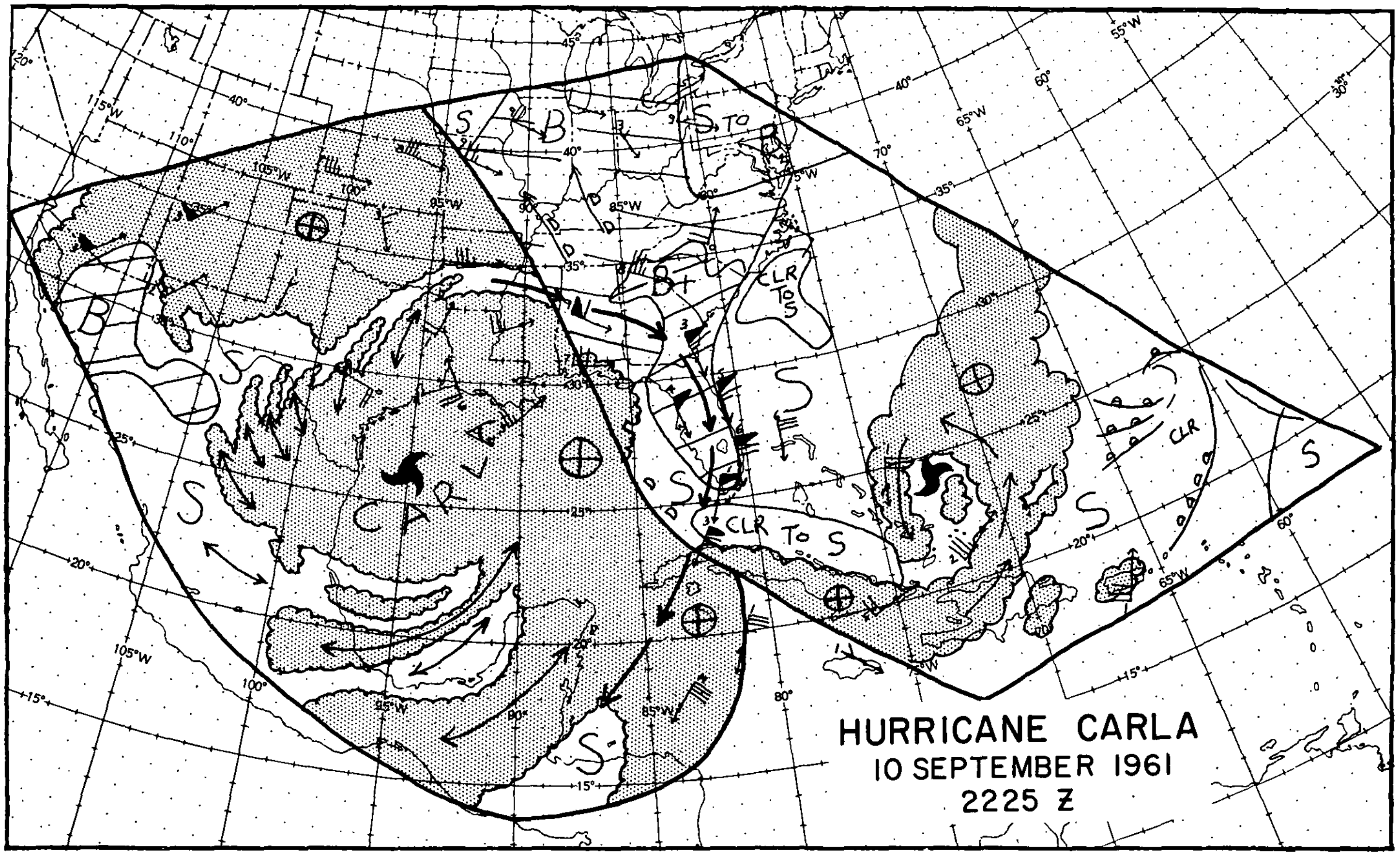

FIGURE 14.—A composite TIROS III nephanalysis from orbital passes 867 and 868. Pictures were taken at 2045 and 2226 GMT, September 10, 1961. Scattered cloud areas are indicated by "S" and broken cloud areas by "B." 200-mb. winds for 0000 GMT, September 11, 1961 are also shown.

information suggests a strong westerly thermal wind effect contributing to the production of a westerly 45-kt. wind at 150 mb.

Several days later, TIROS III was in a position to photograph the "Carla" area. Figure 14 shows a composite nephanalysis obtained from two TIROS III passes over the area of hurricane Carla between 2045 and 2226 GMT on September 10, 1961. The 200-mb. winds for 0000 GMT, September 11, are plotted on this composite for comparison. Of immediate interest is the jet stream which curves anticyclonically at the very edge of the overcast cloudiness of Carla near what has been described as the annular zone of subsidence. (See also fig. 6.) The development of such a high-speed current at upper elevations remote from the center of the storm has been noted in other hurricane studies. Dunn and Miller [3] determined that this effect appeared even in mean data gathered around hurricanes from the 12.5–16.0-km. level. The fact that the feature, at least in this instance, also occurred near the edge of hurricane cloudiness, is a matter of great interest, and possibly of fundamental importance.

Figure 14 also reveals two additional features which should be considered, in relation to cloud forms appearing in the case of hurricane Carla and other TIROS hurricane and typhoon photos. The first concerns the development of a trailing vortex at upper levels. An example of this can be seen in figure 14 near 24° N., 72° W. This cold-core vortex was only weakly apparent at lower levels. It later developed to tropical storm intensity.[6] The second feature concerns the development of trailing convective cloudiness extending toward the equator for long distances. An excellent example of this particular feature is shown in the TIROS V mosaic of typhoon Ruth (fig. 4). (See also fig. 6.) Similar cloudiness is indicated in the nephanalysis of hurricane Carla.

If the development of the hurricane jet, as described, is typical, then it is interesting to consider the appearance of these features in relation to the concept of the conservation of potential vorticity. With constant vorticity and no divergence, there would be a tendency for a trailing vortex to be generated at upper levels, east and generally south of the original storm center. This would occur because of the requirement for the relative vorticity to increase in compensation for the decreasing value of the Coriolis parameter obtained in the southward flow

[6] Frank's [8] independent study of this unnamed tropical storm, involving streamline analysis at the 200-mb. level, established changes of the vortex from cold core cyclonic rotation at 200 mb. to warm core anticyclonic rotation at the same level. The initial upper-level nature of the vortex was established.

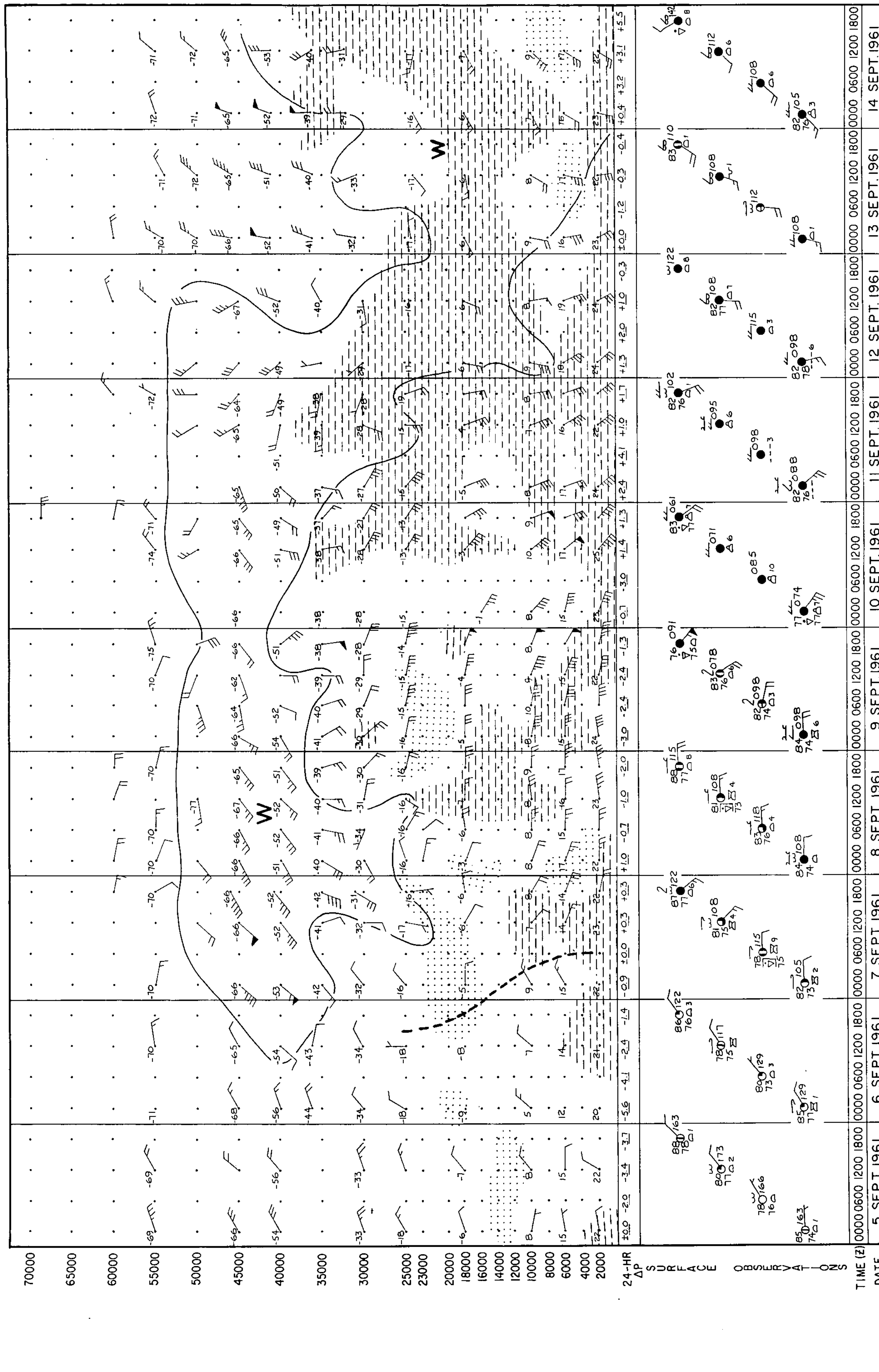

FIGURE 15.—Time cross-section for Burrwood, La. 24-hr. pressure changes are plotted in the middle of the 24-hr. period. Dashed horizontal lines indicate areas with dew point spreads of 5°C. or less. Dotted areas represent dew point spreads of 15°C. or greater. Clear areas, generally below 30,000 ft., have dew point spreads between 5° and 15°C. The 360°–180° isogon is drawn separating easterly flow from westerly flow.

of the jet stream current. The appearance of an upper-level vortex trailing Carla (fig. 14) and in another example (fig. 3) apparently in the process of formation southeast of hurricane Esther, is in agreement with this argument. Flow toward the south or southwest with anticyclonic shear would necessarily be divergent, since anticyclonic vorticity would be acquired in the southward movement of the air mass. The upper-level divergence occurring in an outflow layer of this type, probably at least 10,000 ft. thick, would certainly be favorable for the generation of underlying convective activity. Riehl [12] in fact suggests that the area on the western margin of a southward flowing 200-mb. current is a favorable one for tropical cyclogenesis, because of the pressure falls such a flow would induce "at all levels beneath". Viewed in this light the convective cloudiness trailing Carla (fig. 14), Ruth (fig. 4), and Carmen (fig. 6), is especially interesting.[7] Direction of upper-level flow can sometimes be determined in the TIROS pictures by noting the direction of the shearing anvil tops and the cirrus fringes. Southward flow appears to be indicated south of typhoon Ruth in figure 4. Southwestward flow aloft is clearly revealed in the cirrus striations of the cumulonimbus cloudiness to the south of Carmen (fig. 6). In the case of hurricane Carla the 200-mb. analysis reveals that southward flow also existed, at least east of 90° W., in agreement with the alignment of cloud streaks noted in the nephanalysis.

This concludes, with one exception, the major discussion associating features apparent in the analyses of hurricane Carla, with characteristics suggested by the satellite photographs. The time cross-section analysis for Havana did not clearly show the development of an "outer convective band" or a "pre-hurricane squall line". A line of this type did develop later, however, and is quite apparent in a cross-section analysis for Burrwood, La. (fig. 15). This analysis shows a pronounced squall line effect, shortly after passage of the upper shear zone. Note, in particular, the pronounced dryness of the sounding at 0000 GMT, September 8, following squall line passage. In addition, the development of 60-kt. winds, at upper elevations above the squall line, is certainly a matter of great interest related to the previous discussion. Burrwood, incidentally, was nearly 300 n. mi. from the storm's center, even at time of closest approach of the storm to the station during September 9 and 10.

We may summarize the relevant features found in the various analyses of Carla as follows:

1. Less cloudy conditions existed for at least 48 hr. prior to arrival of the high cloud shield, followed by generally overcast conditions in the hurricane circulation, with clearing again to the rear.

2. Evidence appeared for a trough or squall line of intensified convection in advance of the high cloud shield, indicated on the Burrwood cross-section.

3. The existence of a shear zone at upper elevations was found preceding arrival of the high cloud shield and generally overlying the entire hurricane circulation. The shear zone appeared to move with the hurricane and in fact to define the radial limit of the outflow of the storm.

4. Indications of very dry air at the edge of the hurricane circulation and in the annular area, versus extremely moist air under the high cloud shield, were clearly evident, particularly in the Havana cross-section.

5. Evidence for subsidence along the periphery of the high cloud shield was indicated, over Havana, by temperature increases in the midtroposphere, height rises of pressure surfaces at upper elevations, and indications of falling surface pressure.

6. Winds changed with height from generally steady easterlies prior to passage of the high cloud shield, to easterlies decreasing in speed with height, and finally to high-speed westerlies at the edge of the high cloud shield.

4. TIME CROSS-SECTION FOR SWAN ISLAND AND COMPARATIVE DISCUSSION OF HURRICANE ANNA

The course of hurricane Anna through the Caribbean, in an area of good synoptic coverage, suggested that this would be a promising storm to examine for possible recurrence of the characteristics previously discussed. In addition, the TIROS coverage, at the time, was excellent (fig. 1).

Hurricane Anna apparently formed out of an easterly wave development, reaching hurricane intensity during July 20 and 21, 1961. Early stages of development observed by TIROS III have been described by Fritz [9]. Figure 16 shows the track of this storm as it moved westward from the Lesser Antilles into the Yucatan Peninsula. This same figure shows progressive locations of an advance shear line evident at the 200-mb. level. Features of flow associated with this shear line are clearly revealed in the analysis for this level at 1200 GMT July 21, 1961 (fig. 17). It can be seen in this figure that hurricane Anna was capped by a strong anticyclone. Winds at the periphery of this circulation, 300 to 500 mi. out, exhibited a tendency to be nearly tangential to a circle concentric with the storm center. The shear line at this level was evident, passing northeast-southwest through eastern Cuba and past Jamaica to Costa Rica. Winds of highest speed appeared over San Juan, Puerto Rico along the northern edge of the storm, corresponding, in this instance, to the right rear quadrant of the hurricane.

Cloudiness from hurricane Anna covered a much smaller area than in the instance of Carla and cross-sections showing effects of Anna's passage appear somewhat compressed horizontally, when compared to those of Carla (fig. 18). Nevertheless, many features are revealed which parallel those apparent in hurricane Carla. In particular, the band of westerlies at upper elevations from 0000 GMT, July 22 until 1800 GMT, July 24, appears

[7] Since this paper was originally submitted the case history of typhoon Vera, 1962, has been documented [6]. This storm appeared to develop and intensify under the diverging outflow in the southeastern quadrant of typhoon Ruth.

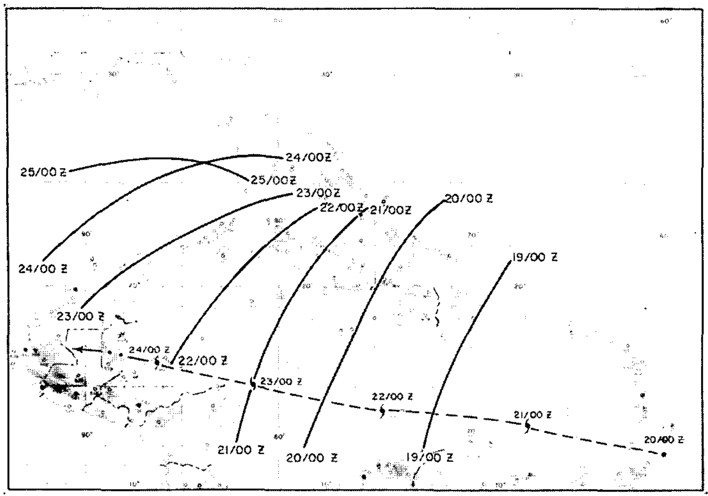

FIGURE 16.—Progressive 300-mb. locations of upper shear line in association with the track of hurricane Anna. Hurricane stages: tropical storm stage (dashed line), hurricane stage (solid line), and depression (dissipation) stage (starred line).

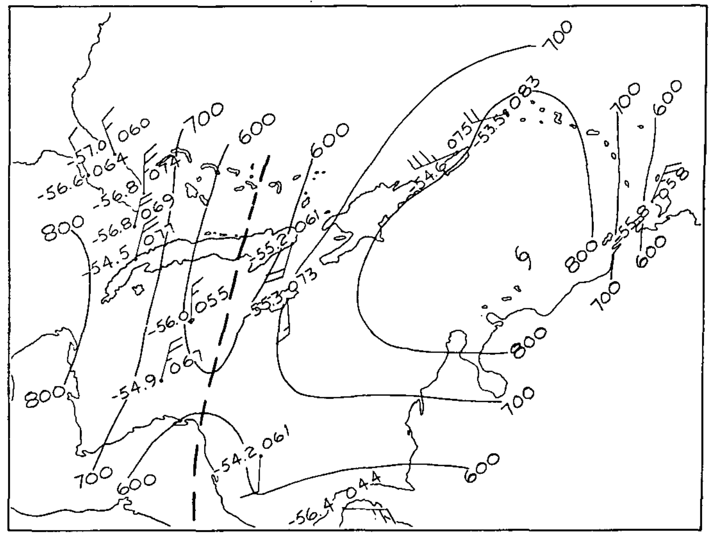

FIGURE 17.—200-mb. analysis for 1200 GMT, July 21, 1961. Contours are drawn in 100-ft. increments. Surface position of hurricane Anna and shear line over Cuba (dashed line) are shown at time of analysis.

derived from the storm circulation, and is nearly centered over the time of closest approach of the storm to the station. This was approximately 1500 GMT July 23. At either end of this band of westerlies, are pronounced dry zones, with dew point spreads indicated in excess of 20°C. A sharp trough is apparent, preceding the dry zone. This trough passed the station between 1200 GMT, July 21 and 0000 GMT, July 22. The synoptic reports during this period suggest the intensified convection one might expect exterior to the annular zone. The TIROS picture of hurricane Anna, shown in figure 1, shows the outer convective band in the southwestern quadrant quite clearly. Swan Island, at the time of this picture (1500 GMT, July 22, 1961) was located approximately 120 n. mi. west of the rim of the high cloud shield. In figure 1 this position is just off the tip of the second cloud mass between the hurricane and the horizon near the top center of the horizon view. This positioning is in good agreement with the location of general features indicated by the time cross-section. Dew point spreads of less than 5°C typify middle levels in the outer convective band area. This is followed by the extremely dry air of the annular zone.

The variation of wind with height, indicated on the cross-section is of special interest. Prior to 1200 GMT, July 21, easterlies backed and increased in speed with height, particularly above the 500-mb. level, indicating cold air advection. However, in the suspected annular zone, at 0000 GMT, July 22, easterlies in middle levels veered and decreased in speed with height. From the 1200 GMT sounding, July 22, it can be seen that lower-level easterlies changed to upper-level westerlies with speeds up to 25 kt. These wind variations lend support to suggested upward vertical motion in the trough area with cooling followed by subsiding motion and warming at the edge of the high cloud shield. Passage of the rim of the high cloud shield over the station presumably occurred at approximately 0900 GMT, July 22. At this time two-tenths total sky coverage was reported consisting of a few low cumuli.

It is notable, in this cross-section, that the highest pressure reported was 1015.8 mb., and that this was recorded approximately 3 hr. prior to passage of the high cloud shield. This same tendency, for highest pressure to occur within 24 hr. of passage of the high cloud shield, was noted in the New Zealand hurricane study [5]. This may be a reflection of the convergence aloft over the annular zone and relates well to the numerous observations verifying pre-hurricane divergence. For stations directly in advance of the storm, when this pattern is obtained, pressure readings should show a tendency for rising 24-hr. pressure changes prior to passage of the high cloud shield, followed by falling 24-hr. pressure changes in the transition zone and as the high cloud shield moves over the station. This pattern did occur for stations in advance of the New Zealand hurricane, and also for Florida stations in advance of hurricane Donna, 1960. This same tendency appears evident in the 24-hr. pressure changes in the cross-section of Swan Island (fig. 18), which shows rising 24-hr. pressure tendencies during the period 1800 GMT, July 21 through 0600 GMT, July 22.

A final item concerns the wind field aloft. No noticeable tendency for an especially high-speed wind, is apparent along the forward (western) edge of this storm. This was also true along the western edge of Carla. However, as in the case of Carla, higher speed winds do appear along the northern quadrants of the storm. This suggests that the thermal contrast between hurricane outflow and

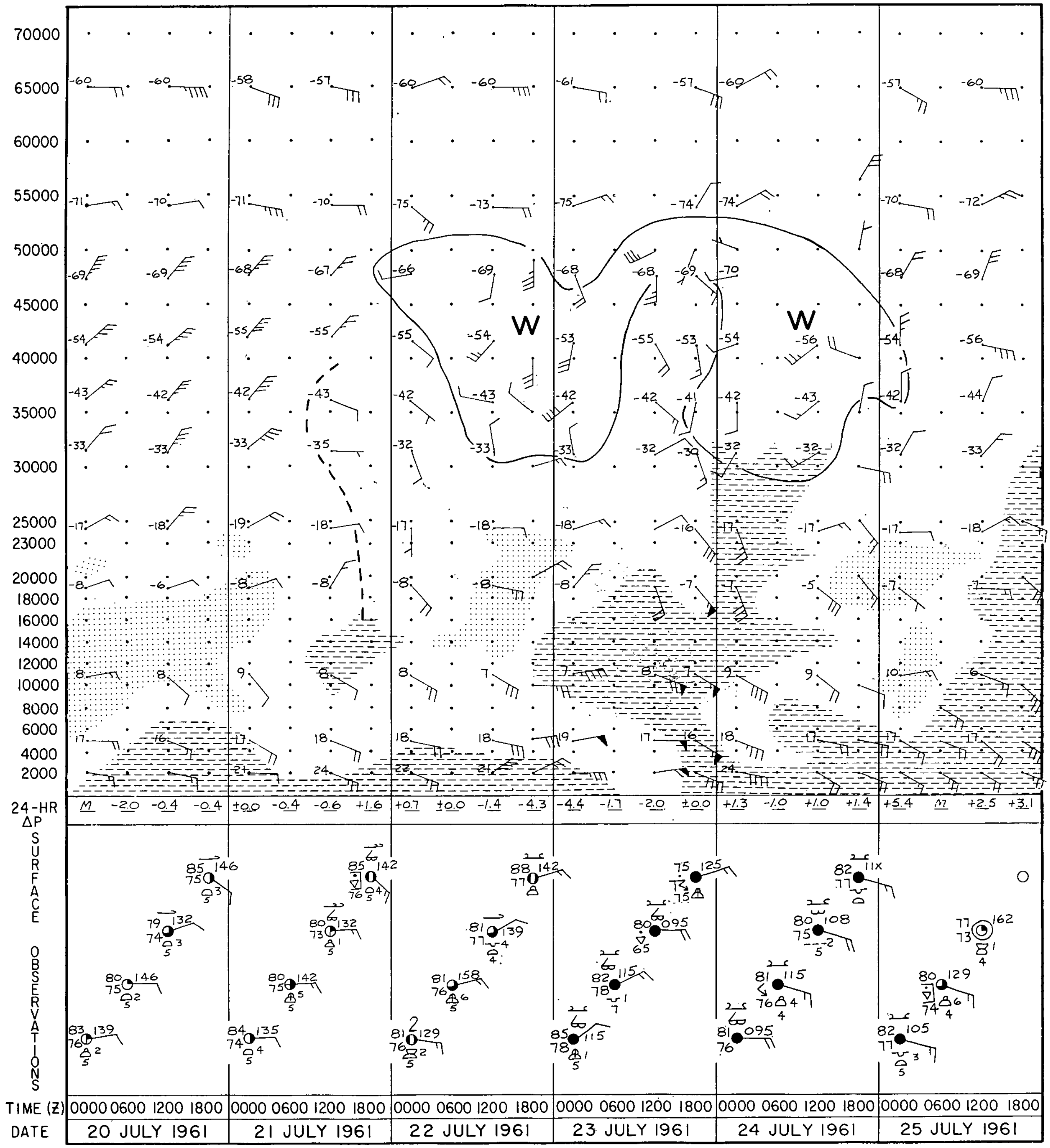

FIGURE 18.—Time cross-section for Swan Island. 24-hr. pressure changes are plotted in the middle of the 24-hr. period. Dashed horizontal lines indicate areas with dew point spreads of 5°C. or less. Dotted areas represent dew point spreads of 15°C. or greater. Clear areas, generally below 30,000 ft., have dew point spreads between 5° and 15°C. The 360°–180° isogon is drawn separating easterly from westerly flow.

that of adjacent high pressure areas is perhaps of dominant importance in the generation of higher speed winds. The effects of vertical motion, according to this view, would play an important, but only an assisting, role.

We may summarize the major characteristics of the hurricane Anna analysis as follows:

1. Hurricane Anna was preceded by a shear zone at upper levels, which appeared to move with the storm.
2. A trough area of intensified convection appeared to precede passage of the edge of hurricane cloudiness.
3. Major hurricane cloudiness appeared limited to the area between dry zones, at either end of a belt of upper westerlies, associated with the outflow layer.
4. The tendency for development of a high-speed wind near the edge of storm cloudiness, at upper levels, was noticeable along the northern quadrants of the storm.
5. Thermal effects due to subsidence and advection, at the edge of hurricane cloudiness, are apparent in the changes in wind velocity with height. The pattern appearing in the cross-section indicated easterly winds, backing and increasing in speed with height, prior to passage of the shear zone aloft. This was followed by easterly winds veering and decreasing in speed with height in the annular zone, becoming westerly in the outflow layer of the hurricane.

5. SUMMARY AND DISCUSSION OF FURTHER IMPLICATIONS

TIROS and Project Mercury hurricane photographs reveal at least two major features which appear to characterize many storms at some time during their development: (1) A relatively clear annular zone of subsidence appears, curving around the rim of the high cloud shield over much of its circumference. (2) A line of intensified convection, or outer convective band, often appears, exterior to the annular zone. This line may vary in intensity and is not always continuous.

A third feature, appearing in some storms as they progress toward higher latitudes, is trailing, convective cloudiness, generating much cirrus. This feature generally appears directed toward the equator in both hemispheres.

This study has reviewed certain arguments, which suggest that the annular zone may be formed through an important subsident branch of the hurricane's circulation. Thermal effects of this subsidence, adjacent to areas of upward vertical motion in the outer convective bands, may aid in the production of a high-speed band of winds, at upper elevations, curving anticyclonically tangential to the edge of hurricane cloudiness. Features of flow associated with shear lines over the annular zones are thought to play a dominant role in the development of these winds. Maximum speed appears to result in the northern and eastern sections of the storm, near the 300–200-mb. level, where the horizontal temperature gradient is strongest. Vorticity considerations applied to the eastern side of the southward flowing jet, favor development of a secondary vortex trailing the original storm, beginning as a disturbance of the upper air. In the instance of the vortex trailing hurricane Carla, continued development to tropical storm intensity resulted. The trailing area of convective, cirrus-producing cloudiness may be initiated as a portion of the southward flowing jet continues in this direction, under the influence of horizontal divergence and near zero vorticity.

The preliminary nature of this study is certainly obvious and must be emphasized. Detailed observations including raobs at least every three hours are desirable for an analysis of peripheral effects. This is necessary since the annular zone, where the major subsidence is occurring, may in certain areas be only 20 mi. in width, and may pass over a given station in a relatively short interval of time. Surface observations should be taken frequently enough, and efforts should be made, to insure recording of the time of passage of the high cloud shield over the station. The existence and intensity of the outer convective bands, as viewed by TIROS, should be studied in relation to radar photographs of the same features. The fact that TIROS can view these bands, since they lie at the periphery of the high cloud shield, is a matter of extreme importance. Tornadic activity, associated with hurricanes, has been shown to develop, primarily, in peripheral regions, possibly in association with the pre-hurricane squall lines or outer convective bands [3]. Satellite observations now permit views which show the location of these bands, over hundreds of miles, and qualitative estimates of relative intensity are certainly possible. It should be noted that conditions in the annular zone, adjacent to these bands, fulfill several of the pre-conditions for tornado development listed by Fawbush and Miller [4]. Among these are: (1) a low-level temperature inversion; (2) sharp vertical moisture stratification; and (3) a narrow band of strong winds aloft.

It is extremely important now that specialized observations be directed to the features observed so that results may be formulated in a quantitative manner.

ACKNOWLEDGMENTS

The author would like to express his appreciation to Dr. Sigmund Fritz and Mr. Lester Hubert, who suggested the initiation of the writing of this paper. Their suggestions, comments, and criticisms spurred much of the research involved. Additional discussions with Mr. Andrew Timchalk, Mr. Thomas Gray, Dr. Harry Johnson, and Mr. Carl Erickson were very helpful. The aid of Mr. Thomas Babicki and Mr. Leonard Hatton in the preparation of figures and that of Mrs. Margaret DiNenna in the preparation of the manuscript is gratefully acknowledged.

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[*Manuscript received September 19, 1962; revised November 26, 1963.*]

Correction Notice

Vol. 91, Nos. 10–12, p. 637: The sentences beginning at bottom of colum 1 should read: "In all figures the Q curve is a plot of increments of pressure corrected optical depth, in centimeters of precipitable water vapor, between successive pressure intervals. This plotted curve utilizes the numerical values of the radiation scale. It is interesting to see the optical depth increments decrease through the cloud, from 570 through 490 mb. in this example."

Figures 2 through 6 on pages 637–639: "mixing ratio Q" should be changed to "optical depth Q."